Example 3i: Asymmetric Laminate

This example problem employs the classical lamination theory capabilities of MAC/GMC 4.0 to simulate the response of an asymmetric SiC/Ti-21S laminate. This fictional laminate consists of four plies, each of which is different. In fact, one layer is monolithic, one layer employs doubly periodic GMC, and the final two layers employ triply periodic GMC. Note that the ability to include doubly and triply periodic layers within the same laminate is a new capability of MAC/GMC 4.0. The laminate is subjected to a midplane strain of 0.02 at 23 °C. The asymmetric lay up of the laminate plies gives rise to non-zero terms in the laminate coupling stiffness matrix [**B**], which induces bending when the laminate is subjected to the applied midplane strain. For more information on the lamination theory and the code's laminate analysis capabilities, see the MAC/GMC 4.0 Theory Manual Section 3.

MAC/GMC Input File: **example_3i.mac**

```
MAC/GMC 4.0 Example 3i - Asymmetric laminate
*CONSTITUENTS
  NMATS=2
  M=1 CMOD=6 MATID=E
  M=2 CMOD=4 MATID=A
*LAMINATE
  NLY=4
  LY=1 MOD=1 THK=0.25 M=2
  LY=2 MOD=2 THK=0.25 ANG=60 ARCHID=6 R=1. VF=0.25 F=1 M=2
  LY=3 MOD=3 THK=0.25 ANG=0. ARCHID=3 ASP1=3. ASP2=2. DR=1. VF=0.25 F=1 M=2
  LY=4 MOD=3 THK=0.25 ANG=0. ARCHID=1 VF=0.25 ASP=1. F=1 M=2
*MECH
  LOP=1
  NPT=2 TI=0.,200. MAG=0.,0.02 MODE=1
*THERM
  NPT=2 TI=0.,200. TEMP=23.,23.
*SOLVER
  METHOD=1 NPT=2 TI=0.,200. STP=0.5
*PRINT
  NPL=6
*XYPLOT
  FREQ=5
  LAMINATE=13
   NAME=example_3i_nxx X=1 Y=10
   NAME=example_3i_nxxp X=1 Y=16
   NAME=example_3i_nyyp X=1 Y=17
   NAME=example_3i_nxyp X=1 Y=18
   NAME=example_3i_mxxp X=1 Y=19
   NAME=example_3i_myyp X=1 Y=20
   NAME=example_3i_mxyp X=1 Y=21
   NAME=example_3i_eyy X=1 Y=2
   NAME=example_3i_ezz X=1 Y=3
   NAME=example_3i_exy X=1 Y=6
   NAME=example_3i_kxx X=1 Y=7
   NAME=example_3i_kyy X=1 Y=8
   NAME=example_3i_kxy X=1 Y=9
  MACRO=0
  MICRO=0
*END
```

Annotated Input Data

1) Flags: None

2) Constituent materials (***CONSTITUENTS**) [KM_2]:

Number of materials:	2	(NMATS=2)
Materials:	SiC fiber	(MATID=E)
	Ti-21S	(MATID=A)
Constitutive models:	SiC fiber: linearly elastic	(CMOD=6)
	Ti-21S matrix: Isotropic GVIPS	(CMOD=4)

3) Analysis type (***LAMINATE**) → Laminate Analysis [KM_3]:

Number of layers: 4 (NLY=4)

Layer	Analysis Model	Thickness	Fiber Angle	Architecture	Volume fraction	Aspect ratio	Fiber material	Matrix material
(LY)	(MOD)	(THK)	(ANG)	(ARCHID)	(VF)	(R)	(F)	(M)
1	monolithic	0.25	–	–	–	–	–	Ti-21S
2	GMC-2D	0.25	60°	7×7 circle, rect. pack	0.25	1.	SiC	Ti-21S
3	GMC-3D	0.25	0°	off-set fibers (3)	0.25	–	SiC	Ti-21S
4	GMC-3D	0.25	0°	short fiber (1)	0.25	–	SiC	Ti-21S

<u>Additional information for layers 3 and 4</u>:

Fiber aspect ratio	3.	(ASP1=3.)
Unit cell aspect ratio:	2. or 1.	(ASP2=2. or ASP=1.)
D ratio (ARCHID=3 only):	1.	(DR=1.)

The laminate in this example problem consists of a monolithic Ti-21S layer and three composite SiC/Ti-21S layers: a 60° continuous layer, a short fiber discontinuous layer, and a particulate discontinuous layer. For more information on the laminate analysis input requirements, see the MAC/GMC 4.0 Keywords Manual Section 3.

4) Loading:

a) Mechanical (***MECH**) [KM_4]:

Loading option:	1 (loading in the laminate x-direction)	(LOP=1)
Number of points:	2	(NPT=2)
Time points:	0., 200. sec.	(TI=0.,200.)
Load magnitude:	0., 0.02	(MAG=0.,0.02)
Loading mode:	midplane strain/curvature control	(MODE=1)

b) Thermal (***THERM**) [KM_4]:

Number of points:	2	(NPT=2)
Time points:	0., 200. sec.	(TI=0.,200.)
Temperature points:	23., 23. °C	(TEMP=23.,23.)

c) Time integration (***SOLVER**) [KM_4]:

Time integration method:	Forward Euler	(METHOD=1)
Number of points:	2	(NPT=2)
Time points:	0., 200. sec.	(TI=0.,200.)
Time step sizes:	0.5 sec.	(STP=0.5)

5) Damage and Failure: None

6) Output:

a) Output file print level (***PRINT**) [KM_6]:

Print level:	6	(NPL=6)

b) x-y plots (***XYPLOT**) [KM_6]:

Frequency:	5	(FREQ=5)
Number of laminate plots:	13	(LAMINATE=13)
Laminate plot names:	example_3i_nxx	(NAME=example_3i_nxx)
	example_3i_nxxp	(NAME=example_3i_nxxp)
	example_3i_nyyp	(NAME=example_3i_nyyp)
	example_3i_nxyp	(NAME=example_3i_nxyp)
	example_3i_mxxp	(NAME=example_3i_mxxp)
	example_3i_myyp	(NAME=example_3i_myyp)
	example_3i_mxyp	(NAME=example_3i_mxyp)
	example_3i_eyy	(NAME=example_3i_eyy)
	example_3i_ezz	(NAME=example_3i_ezz)
	example_3i_exy	(NAME=example_3i_exy)
	example_3i_kxx	(NAME=example_3i_kxx)
	example_3i_kyy	(NAME=example_3i_kyy)
	example_3i_kxy	(NAME=example_3i_kxy)
Laminate plot quantities:	ε^0_{xx} , N_{xx}	(X=1 Y=10)
	ε^0_{xx} , N^p_{xx}	(X=1 Y=16)
	ε^0_{xx} , N^p_{yy}	(X=1 Y=17)
	ε^0_{xx} , N^p_{xy}	(X=1 Y=18)
	ε^0_{xx} , M^p_{xx}	(X=1 Y=19)
	ε^0_{xx} , M^p_{yy}	(X=1 Y=20)
	ε^0_{xx} , M^p_{xy}	(X=1 Y=21)
	ε^0_{xx} , ε^0_{yy}	(X=1 Y=2)
	ε^0_{xx} , ε^0_{xy}	(X=1 Y=3)
	ε^0_{xx} , $\bar{\varepsilon}_{zz}$	(X=1 Y=6)
	ε^0_{xx} , κ^0_{xx}	(X=1 Y=7)
	ε^0_{xx} , κ^0_{yy}	(X=1 Y=8)
	ε^0_{xx} , κ^0_{xy}	(X=1 Y=9)

Number of macro plots: 0 (MACRO=0)
Number of micro plots: 0 (MICRO=0)

7) End of file keyword: (***END**)

Results

Table 3.2 shows that the asymmetric laminate **ABD** matrix is fully populated. Thus, due to the applied normal midplane strain, global shear strains (due to the presence of the 60° layer), as well as bending (due to the laminate's asymmetry) will result.

Figure 3.18 shows plots of the laminate force resultant (N_{xx}) and laminate inelastic force resultants (N_{ij}^{p}) that arise due to the applied normal midplane strain. The point at which the laminate yields is clear in this figure as the inelastic force resultants begin to arise. Also, the inelastic shear force resultant is small relative to the normal inelastic force resultants. Figure 3.19 shows the laminate inelastic moment resultants (M_{ij}^{p}) that rise during the MAC/GMC 4.0 simulation (which are an indicator of inelastic laminate bending). Again, it is clear that the shear component is smaller than the normal components. The inelastic bending moment component associated with the loading direction (M_{xx}^{p}) appears to be the dominant component, and several reversals in the M_{xx}^{p} history occur during the simulation. These reversals are caused by the onset and progression of inelastic deformation in the layers of the laminate as it bends. Figure 3.20 shows the midplane strain and curvature components that arise in the laminate during the simulation. Again, the shear components are less significant than the normal components. The normal curvature histories exhibit reversals in slope, as do the normal inelastic moment results plotted in Figure 3.19.

Table 3.2 Example 3i: effective stiffness and engineering constant results for the asymmetric SiC/Ti-21S laminate analyzed taken from the MAC/GMC 4.0 output file.

Asymmetric Laminate
Laminate Axial Stiffness Matrix [A] 2.342E+04 8.364E+03 8.295E+01 8.364E+03 2.392E+04 4.308E+02 8.295E+01 4.308E+02 7.570E+03 Laminate Coupling Stiffness Matrix [B] 6.044E+02 1.239E+02 -1.037E+01 1.239E+02 5.176E+02 -5.385E+01 -1.037E+01 -5.385E+01 1.024E+02 Laminate Bending Stiffness Matrix [D] 1.888E+03 6.630E+02 1.728E+00 6.630E+02 1.898E+03 8.974E+00 1.728E+00 8.974E+00 5.857E+02 Laminate Engineering Constants (only valid for symmetric laminates) E11= 2.029E+04 N12= 3.515E-01 E22= 2.074E+04 G12= 7.541E+03

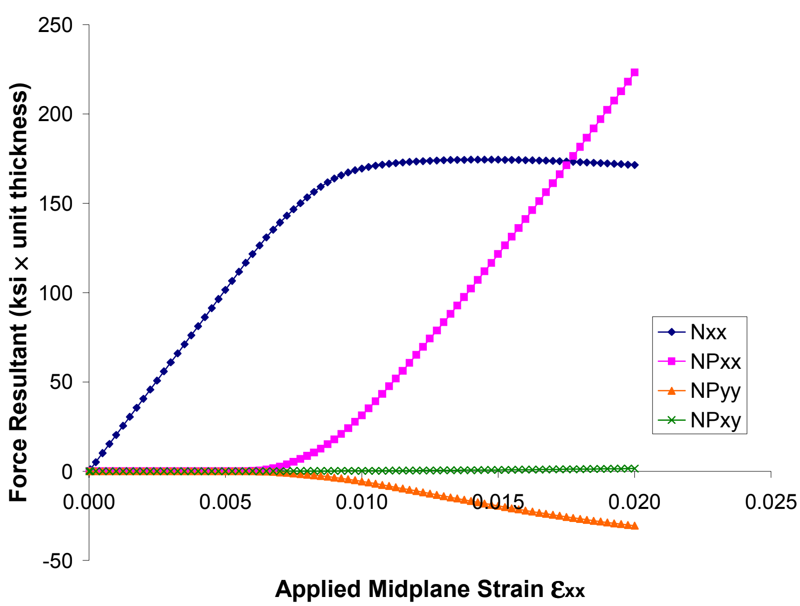

Figure 3.18 Example 3i: plot of the global force resultant (N) and inelastic force resultant (NP) response for an asymmetric SiC/Ti-21S laminate at 23 °C to an applied midplane strain.

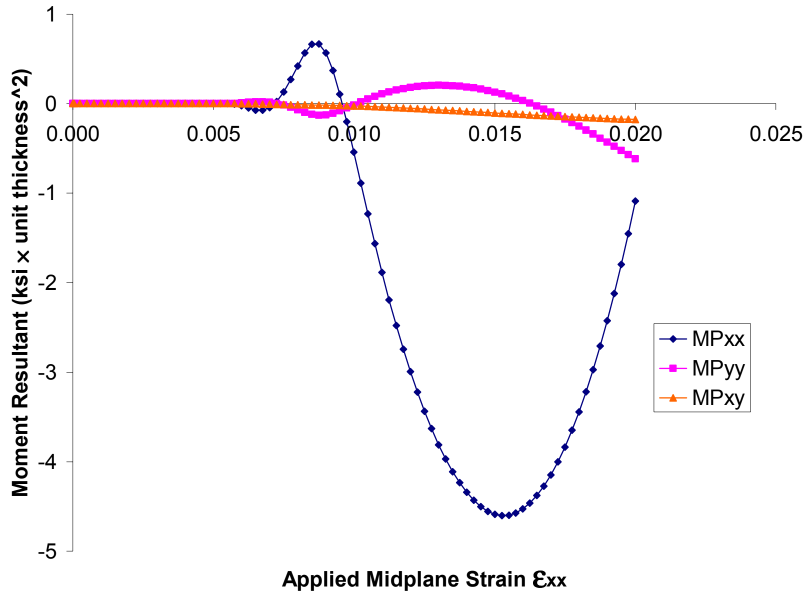

Figure 3.19 Example 3i: plot of the global inelastic moment resultant (MP) response for an asymmetric SiC/Ti-21S laminate at 23 °C to an applied midplane strain.

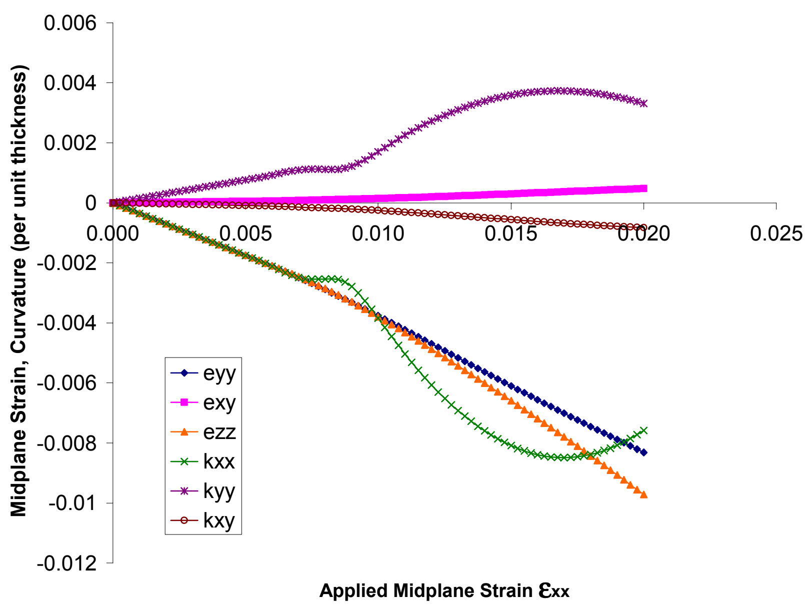

Figure 3.20 Example 3i: plot of the global midplane strain (e) and midplane curvature (k) response for an asymmetric SiC/Ti-21S laminate at 23 °C to an applied midplane strain.